an assumed offset of zero degrees yields sufficient results and significantly reduced complexity of the resulting dynamic equations of motion.

[0066] Pronosupination of the forearm can be treated interchangeably as a freedom of the elbow and as a freedom of the wrist. In either case, it is considered directly adjacent to the forearm, occurring after elbow flexion and before either wrist flexion or deviation, with the axis of rotation running approximately through the 5th metacarpal-phalangeal joint.

[0067] The wrist can be modeled as two orthogonal axes with a fixed offset between them. The proximal and distal axes of the wrist correspond to wrist flexion-extension and wrist radial-ulnar deviation, respectively.

[0068] Although, anthropometrically, the wrist could be more accurately represented incorporating a slight offset between the flexion-extension and radial-ulnar deviation axes, this offset was neglected for simplicity. Unlike the neglected forearm offset, β, which was unnoticeable to the user, the high sensitivity of the wrist joint to changes in position and torque make this human-machine discrepancy mildly noticeable.

[0069] For one example of the present subject matter, the anatomic joints of the human upper limb are defined as ball/socket type of joints. In order to meet the requirements of an anthropomorphic joint design for the exoskeleton, the line of rotation of the exoskeleton joints coincide with the anatomical axis. For example in the shoulder joint, the two orthogonal rotation axes cross each other at a virtual point where the humeral head is rotating relative to the glenoid fossa (socket of shoulder joint). In addition, the third axis of rotation lies along the humerus bone allowing the anatomic motion of internal and external rotation. The length of the exoskeleton links can be adjustable to accommodate differences in the anthropomorphic arm dimensions. Moreover, in order to prevent injuries to the operator's joints, such as joint dislocation, the anatomical joints' range of motion is incorporated into the design of the exoskeleton joints. This assures that the range of motion of the exoskeleton joints will never exceed the range of motion of the operator.

[0070] A 7-DOF model of the human arm includes three segments (upper arm, lower arm and the hand) connected to each other and the human trunk with a frictionless ball-and-socket shoulder joint, 2-axis elbow and 2-axis wrist. Using this structure, 7 equations of motion can be written. The mass, the center of mass location, and the inertia of the human arm segments can be estimated for each subject. The general form of the equations of motion is expressed in Equation 1.

$$\tau = M(\Theta)\ddot{\Theta} + V(\Theta,\dot{\Theta}) + G(\Theta) \quad (1)$$

where $M(\Theta)$ is the 7×7 mass matrix, $V(\Theta,\dot{\Theta})$ is a 7×1 vector of centrifugal and Coriolis terms, $G(\Theta)$ is a 7×1 vector of gravity terms, and τ is a 7×1 vector of the net torques applied at the joints. Given the kinematics ofthe human arm $(\Theta,\dot{\Theta},\ddot{\Theta})$ the individual contributions on the net joint toque (τ) vector can be calculated for each action of each subject. The net torque can be calculated from the contribution of the individual components (inertial, centrifugal, and Coriolis, and gravity).

[0071] Various muscle models exist that provide a quantitative representation of contraction dynamics. Such models differ in intended application, mathematical complexity, level of structure considered and fidelity to the biological facts. Some muscle models include 1) microscopic models; 2) distributed moment models; 3) macroscopic models; 4) fiber models. Hill-based models, viscoelastic models, and system models are subcategories of the macroscopic models class.

[0072] In various examples of the present subject matter, the muscle is modeled using two macroscopic muscle models including a Hill-based muscle model and neural network model as part of a HMI for a single degree-of-freedom (DOF) powered exoskeleton.

[0073] During certain positioning tasks, higher angular velocities are observed in the gross manipulation joints (the shoulder and elbow) as compared to the fine manipulation joints (the wrist). An inverted phenomenon is noted during fine manipulation in which the angular velocities of the wrist joint exceeded the angular velocities of the shoulder and elbow joints. Analyzing the contribution of individual terms of the arm's equations of motion indicate that the gravitational term is the most dominant term in these equations. The magnitudes of this term across the joints and the various actions is higher than the inertial, centrifugal, and Coriolis terms combined. Variation in object grasping (e.g. power grasp of a spoon) alters the overall arm kinematics in which other joints, such as the shoulder joint, compensate for lost dexterity of the wrist. The collected database along with the kinematics and dynamic analysis provide the fundamental understanding for designing the powered exoskeleton for the human arm as well as the effect of joint compensations in case of disability.

[0074] It has been stated that to achieve proper correlation between Euler angle model representations and the actual biomechanics of the arm, forearm pronosupination should precede both wrist flexion and deviation axes.

[0075] The Vicon axes designated in FIG. **3** as axes **5**, **6**, and **7** cannot be directly compared to anatomical motions of wrist flexion, deviation, and rotation. They can instead be considered as a set, with axes **5** and **6** only corresponding to flexion-extension and radial-ulnar deviation when pronosupination is near zero, and axis **7** only corresponding to pronosupination when both wrist flexion and deviation are near zero.

[0076] In general, the largest ranges of motion during daily tasks are found in elbow flexion-extension and forearm pronosupination, each at 150 degrees, while the requirement from shoulder flexion-extension, the joint having the largest physiological range of motion, remains less at 110 degrees. Average joint torques seen in the elbow and wrist are approximately one tenth and one one-hundredth, respectively, of those experienced at the shoulder, with median torques at the shoulder ranging from 0.4 to 4 Nm.

II. EXOSKELETON STRUCTURE

[0077] This section describes the skeleton (orthotic device) mechanism itself and its biomechanical integration with the human body

[0078] The present subject matter can be configured to have a variety of degrees of freedom. For example, the system can be configured for 1-DOF, 3-DOF, or 7-DOF. In various examples, system is controlled based on surface